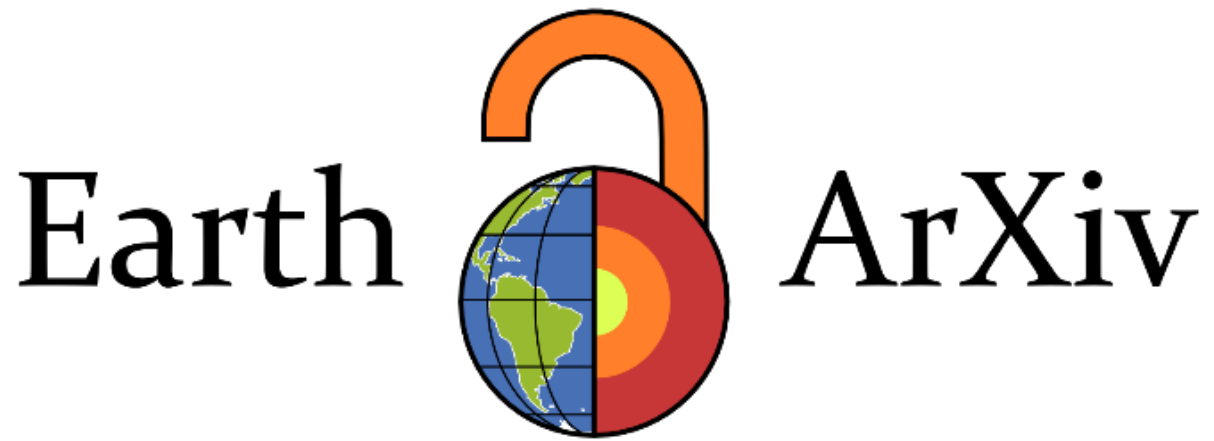




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Fault roughness as a driver of rupture complexity in fluid-induced microearthquakes

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Key Points:

- We quantify the combined effects of fault topography and available energy on the propagation of fluid-induced microearthquakes.
- 1395 three-dimensional dynamic rupture simulations reveal highly complex rupture kinematics even for $M_w \sim 1$ earthquakes.
- Fault geometric complexity should be considered when assessing seismic hazard during geo-energy resource development.

Abstract

Subsurface fluid-injection can induce microearthquakes whose rupture complexity and arrest mechanisms remain poorly understood, limiting our ability to assess the seismic hazard associated with geo-energy applications. We investigate how fault roughness modulates the response of fluid-pressurized faults using an ensemble of 1395 3D dynamic rupture simulations on self-similar rough faults, varying the maximum roughness wavelength, roughness amplitude, and dynamic friction. We show that rupture propagation and arrest are governed by a competition between the large-scale heterogeneity imposed by the pore-pressure gradient and the local shear and normal stress heterogeneity generated by variations in fault geometry. Our results demonstrate that dynamic rupture complexity emerges already at the scale of $M_w \sim 1$ fluid-induced microearthquakes, with fault roughness promoting acceleration and deceleration phases and, in some cases, pulse-like rupture behavior. The maximum roughness wavelength controls rupture complexity by determining the effectiveness of asperities and barriers, thereby constraining rupture growth and maximum attainable magnitude. Simulated magnitudes are inherently bimodal, with fault roughness and friction dictate the critical transition from failed nucleations to self-arresting and runaway ruptures. Furthermore, smoother faults, characterized by lower roughness amplitudes, progressively build up higher loading conditions at the rupture front, favoring coherent ruptures exhibiting predominantly crack-like propagation. Fault roughness affects stress redistribution and produces spatial variations in the local energy balance driving rupture front propagation, evidenced by spatial variations in cohesive zone size and rupture velocity. These findings indicate that reliable estimates of the maximum size of induced earthquakes must account for initial stress conditions as well as fault geometric complexity.

Plain Language Summary

Injecting fluids deep underground is a common practice for modern clean-energy resources, such as geothermal energy. However, this process can sometimes trigger earthquakes. Scientists still do not fully understand how these small earthquakes grow, move, and eventually stop, which makes it difficult to accurately predict the safety risks associated with these energy projects. In this study, we used advanced 3D computer simulations to look at how rough fault surface topography affects these fluid-triggered earthquakes. We found that even very small earthquakes are highly complex. As an earthquake moves along a rough fault, the roughness causes it to constantly accelerate and decelerate. The size of the largest bumps on a fault is especially important because the largest-scale geometric features can act as barriers, limiting how far the earthquake can spread and how large it can ultimately become. In contrast, smoother faults allow energy to build up more steadily, leading to continuously propagating earthquakes. Ultimately, our findings show that to estimate how large an induced earthquake could get, we cannot just consider the underground fluid pressure injection. We must also account for the shape of the faults themselves. This knowledge is crucial for designing safer and more reliable underground energy technologies.

1 Introduction

Fault geometric heterogeneity, acting across multiple spatial scales, exerts a fundamental control on earthquake rupture dynamics and the resulting radiated wavefields (Dunham et al., 2011; Shi & Day, 2013). At the macroscale, natural faults depart from planar geometries, displaying multi-scale structural complexity (Ben-Zion & Sammis, 2003). This geometric deviation spans from regional-scale segmentation and step-overs, down to sub-millimeter topographic roughness along the principal slip zone (Candela et al., 2012; Renard et al., 2013).

The essential effect of fault roughness is to induce local variations in fault stress, both during and between seismic events (Chester & Chester, 2000; Fang & Dunham, 2013). Specifically, local variations in both shear and normal stress are induced when resolving the initial ambient stress field onto a non-planar fault surface. In addition, during dynamic slip, the mechanical forcing of rupture overriding topographic asperities causes localized clamping and unclamping. These stress heterogeneities can strongly influence rupture nucleation (Cattania & Segall, 2021), propagation and arrest, driving complex behaviors, such as the emergence of multiple slip pulses during rupture (Tal et al., 2018). By continuously accelerating and decelerating the rupture front during propagation, these variations can generate heterogeneous slip distributions (Dieterich & Smith, 2009; Bruhat et al., 2020), and can trigger transient burst to supershear rupture speeds (Bruhat et al., 2016). Such intermittent rupture behavior has been proposed as an important mechanism for generating high-frequency seismic radiation (Madariaga, 1977; Dunham et al., 2011; Shi & Day, 2013; Taufiqurrahman et al., 2022; Gallovič & Valentová, 2023).

While these effects have been extensively investigated in the context of tectonic earthquakes, their role in fluid-induced seismicity remains comparatively less studied (Maurer et al., 2020). Subsurface fluid injection can induce seismic events, as widely documented in different tectonic settings and geo-resource exploitation activities (Ellsworth, 2013). As fluid injection/production operations expand to meet growing energy demands, quantifying the associated seismic hazard becomes increasingly critical, particularly for oil and gas production, CO_2 sequestration, and enhanced geothermal systems (Candela et al., 2018; Moein et al., 2023). A key challenge is constraining the potential maximum magnitude of induced earthquakes (McGarr, 2014; Galis et al., 2017), which requires a better understanding of physical mechanisms governing fluid-induced ruptures. In this context, the role of fault roughness under both dry and fluid-pressurized conditions is of particular interest for the safe exploitation of geo-resources.

Numerous studies leveraging observed data, laboratory experiments and numerical modeling have investigated fluid-induced earthquakes (Garagash & Germanovich, 2012; Gischig, 2015; Cappa et al., 2019; Palgunadi et al., 2020; Ciardo & Rinaldi, 2022; Sáez & Lecampion, 2024). However, how large-scale, pore-pressure-induced stress gradients interact with roughness-induced local stress heterogeneities during 3D dynamic fluid-induced ruptures remains mostly unexplored. Existing laboratory experiments nevertheless highlight the importance of fault roughness and stress heterogeneity, demonstrating that both not only control the clustering of lab-quakes around localized asperities and their source characteristics (Wang et al., 2024), but also drive fabric evolution, thereby modifying the frictional strength and hydro-mechanical properties of granular materials (Scuderi et al., 2025). Consistent with these observations, Maurer et al. (2020) showed through 2D dynamic rupture simulations, for earthquake magnitude $3.5 \leq M_w \leq 4.6$, that fault roughness can exert a primary control on rupture arrest, whereas pore-pressure becomes dominant only under specific conditions of low fluid over-pressure.

Accurately characterizing micro-earthquakes' mechanics is also becoming increasingly important for better understanding fundamental earthquake physics and constraining scaling laws governing source parameters (e.g., Gabriel et al. (2024); Mosconi et al. (2025)). Fluid-induced seismicity in geothermal reservoirs and hydraulic stimulation operations offers the opportunity to study rupture processes under controlled conditions. Recent developments in underground research infrastructures have enabled in-situ large-scale induced-seismicity experiments (Kwiatek et al., 2018; Guglielmi et al., 2021; Ma et al., 2021; De Barros et al., 2023). These experiments provide high-quality multidisciplinary observations from dense on-fault monitoring systems, allowing detailed observational investigations of microearthquakes (Meier et al., 2026).

Yet, a comprehensive analysis of the influence of 3D fault geometric complexity on the dynamics of fluid-induced microearthquakes is lacking. Our study is further motivated by the need to understand how the intrinsic stress gradients imposed by pore-pressure

perturbations interact with local stress heterogeneity induced by fault topography, to dictate dynamic rupture front acceleration, deceleration and arrest. Whereas previous studies have shown that pore-pressure-induced stress gradients play a fundamental role in controlling dynamic rupture extent (Mosconi et al., 2025, 2026), it remains unclear how their influence compares with that of roughness-induced stress heterogeneity. In this study, we investigate how dynamic ruptures propagating on rough faults during microearthquakes under heterogeneous prestress conditions may either spontaneously arrest within the pressurized region (“self-arresting”) or evolve into “runaway” ruptures that propagate beyond the fluid-stimulated area. Understanding this transition is critical for estimating the maximum magnitude of induced earthquakes in EGS (Enhanced Geothermal System) and CCS (Carbon Capture and Storage) operations, beyond predictions based solely on injected fluid volume.

2 Methods

2.1 Rough Fault Geometry and Computational Domain

We adopt a reference 60×50 m, 60° dipping normal fault plane, to generate a set of rough faults by introducing 2D band-limited roughness as normal perturbations. Observations of natural fault surfaces reveal roughness over a wide range of spatial scales (W. Power et al., 1987; Candela et al., 2009; Bistacchi et al., 2011). Over specific wavelength bands, fault topography is commonly described as a self-affine fractal surface, characterized by a Hurst exponent H that typically ranges between 0.6 and 0.8 (Candela et al., 2012). In the spectral domain, self-affine roughness is associated with a power-law decay of the power spectral density:

$$P(k) \propto k^{-\beta}, \quad (1)$$

where k is the wavenumber, $\beta = 2H + 1$ in the 1D case. However, when considering the full range of observations, a value closer to $H \approx 1$ better captures both large- and intermediate-scale roughness (Shi & Day, 2013). Accordingly, we adopt $H = 1$.

The fault surface is modeled as a 2D band-limited fractal topography (implementation details are provided in the Supplementary Material), with wavelengths in the range $[\lambda_{\min}, \lambda_{\max}]$. We fix $\lambda_{\min} = 0.4$ m in all simulations and vary $\lambda_{\max}$ within $\{20, 25, 30, 35, 40\}$ m to explore the effect of heterogeneity length scale. When $\lambda_{\max}$ is smaller, geometric variability is confined to relatively small spatial scales on the fault plane (Figure 1b), as $\lambda_{\max}$ increases, progressively larger-scale geometric features are introduced.

Another key parameter is the roughness amplitude-to-wavelength ratio, $\alpha = h_{\text{rms}}/L$, where h_{rms} is the root-mean-square amplitude of the roughness profile and L is the total fault length in the down-dip direction. In natural faults, α typically ranges between 10^{-3} and 10^{-2} (W. L. Power & Tullis, 1991). To capture this variability, we consider $\alpha = [0.004, 0.006, 0.008]$. Increasing α leads to a systematic amplification of roughness amplitude, as illustrated in Figure 1b.

We embed the fault in a homogeneous 3D elastic medium (Figure 1a), characterized by compressional (v_p) and shear (v_s) wave velocities of 2612 m/s and 1513 m/s, respectively, and density $\rho = 2620$ kg/m³, in a $250 \times 250 \times 250$ m computational domain (details on the unstructured tetrahedral meshes and resolution are provided in the Supplementary Material).

2.2 3D Dynamic Rupture

We model the 3D dynamic rupture of fluid-induced micro-earthquakes on rough faults using SeisSol (Gabriel et al., 2025b), an efficient open-source software package, optimized for modern HPC infrastructures (e.g., Dorozhinskii & Bader, 2021). SeisSol implements the arbitrary high-order DERivative Discontinuous Galerkin (ADER-DG) scheme

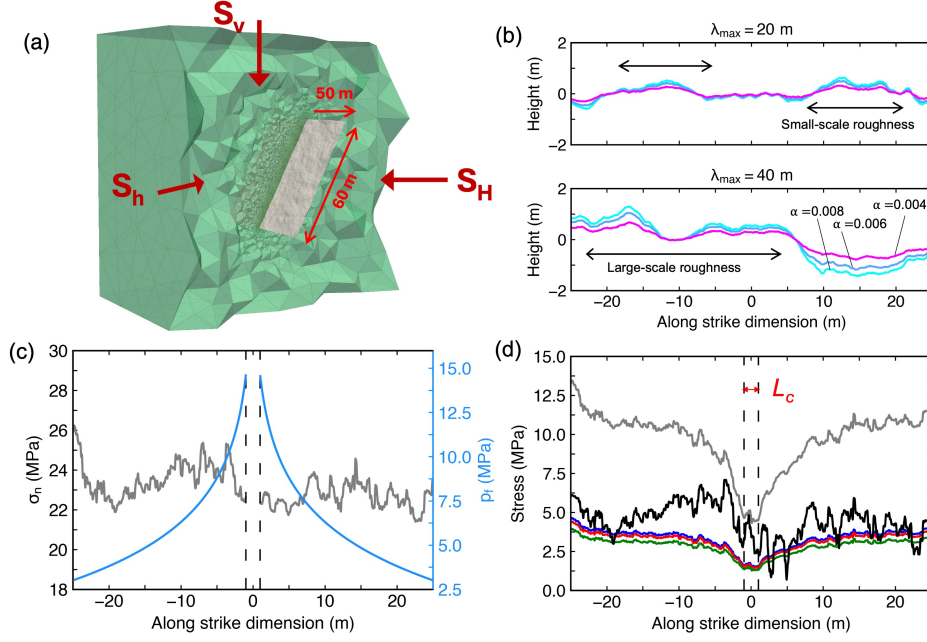


Figure 1. 3D rough fault model geometry and initial stress conditions. **a)** Clipped view of a representative unstructured mesh, showing the embedded rough fault, and the orientation of the principal stresses. **b)** Fault topography for a 1D section along fault strike, colored by roughness amplitude (α). The upper panel shows the roughness for $\lambda_{\max} = 20$ m, while the lower panel shows the $\lambda_{\max} = 40$ m profile. **c)** Normal stress for an 1D section along fault strike (gray line) for $\lambda_{\max} = 40$ m and $\alpha = 0.008$ (background stress only). Cyan line shows the imposed radial pore-pressure distribution (p_f), resulting from a coupled hydromechanical simulation of constant flow-rate injection. **d)** Overall stress conditions for 1D fault along strike section, for $\lambda_{\max} = 40$ m and $\alpha = 0.008$. The gray line shows the static strength τ_p , the black line shows the initial shear stress τ_0 , and the blue, red and green lines the dynamic strength τ_r for $\mu_d = 0.20, 0.19$ and 0.17 respectively.

(Dumbser & Käser, 2006) to simultaneously solve for fault frictional failure and seismic wave propagation (Pelties et al., 2014; Uphoff et al., 2017). SeisSol employs statically adaptive, unstructured tetrahedral meshes, enabling the representation of geometrically complex fault systems, including non-planar fault geometries embedded within 3D volumes.

We adopt a linear slip-weakening constitutive law to describe the evolution of shear stress, τ , with slip, δ , at the rupture tip (Ida, 1972; Andrews, 1976). This constitutive law is characterized by three parameters: the critical slip distance, d_c , and the static and dynamic friction coefficients, μ_s and μ_d . We assume $d_c = 0.6$ mm and $\mu_s = 0.58$, same as Mosconi et al. (2026). To investigate the effect of the dynamic stress drop on rupture behavior, we consider three values of μ_d : 0.17, 0.19, and 0.20 according to Mosconi et al. (2025). Defining the residual shear stress as $\tau_r = \mu_d(\sigma_n - p_f)$, where σ_n is the normal stress and p_f is the pore-fluid pressure, the corresponding dynamic stress drop is given by $\Delta\tau_d = \tau_0 - \tau_r$, where τ_0 denotes the initial shear stress.

The linear slip-weakening formulation has the advantage of prescribing the fracture energy G_c , i.e., the energy dissipated during rupture propagation, defined as:

$$G_c = \frac{1}{2}(\tau_p - \tau_r)d_c. \quad (2)$$

where τ_p is the peak shear stress.

For each combination of μ_d , $\lambda_{\max}$, and α , we generate 31 random realizations of fault roughness (using identical seeds across parameter sets), resulting in a total of 1395 dynamic rupture simulations. A detailed list of all the explored parameters and initial conditions can be found in the Supplementary Material. Rupture nucleation is not modeled spontaneously. Instead, rupture is initiated by imposing localized overstress at the fault center, corresponding to the injection point, within a circular patch of 1 m radius (black dashed lines in Figure 1c–d; see Supplementary Material for details).

2.3 Stress Conditions and Injection Scenario

Resolving regional stress field onto the rough fault geometry naturally induces highly variable initial local tractions. To obtain a realistic representation of the stress state acting on the modeled fault, we adopt the background principal stress orientations and magnitudes constrained by the Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG) model (Bröker et al., 2024). The imposed stress regime corresponds to a normal-faulting setting, with $S_h < S_H < S_v$, where S_h is the minimum horizontal stress (20 MPa), oriented perpendicular to the fault, S_H is the maximum horizontal stress (25 MPa), oriented parallel to the fault, and S_v is the vertical stress (31 MPa). Under these conditions, for a planar fault and neglecting pore pressure (p_f), the resulting normal stress is $\sigma_n^{planar} = 22.7$ MPa (positive in compression), while the initial shear stress is $\tau_0^{planar} = 4.7$ MPa.

When a rough fault surface is considered, characterized by a zero-mean root-mean-square roughness (Dunham et al., 2011), both σ_n and τ_0 , perturbed by geometric irregularities, fluctuate around mean values corresponding to those of the planar fault. Under dry conditions, Figure 1c shows the distribution of σ_n (prior to injection) along a 1D along-strike section of the fault for $\lambda_{\max} = 20$ m and $\alpha = 0.008$. Long-wavelength perturbations dominate the absolute magnitude of the stress variations (~ 2 MPa), whereas shorter-wavelength fluctuations introduce high-frequency traction oscillations, consistent with the power spectral density described by Equation 1.

The fault is subsequently perturbed by a pore-pressure field obtained from coupled hydromechanical simulations of constant flow-rate injection (0.012 kg/s), which maintain $p_f = 14.5$ MPa at the injection point. These simulations are performed using the TOUGH3-FLAC3D framework (Rinaldi et al., 2022), and the resulting pore-pressure distribution is then imposed as a static field in the dynamic rupture simulations, following (Mosconi et al., 2025). With the injection point located at the fault center, pore pressure decreases radially from a maximum value of 14.5 MPa toward the ambient pressure $p_0 = 3.8$ MPa (Figure 1c). Further details on the injection protocol are provided in the Supplementary Material.

Within the linear slip-weakening framework, thus the imposed pore-pressure field modifies the effective normal stress ($\sigma'_n = \sigma_n - p_f$), both τ_p and τ_r also vary. As a result, the large-scale pore-pressure gradient is superimposed on the smaller-scale stress heterogeneity generated by fault roughness, producing spatial variations in all τ_p , τ_r , and τ_0 (Figure 1d).

The relative prestress ratio R (Aochi & Madariaga, 2003):

$$R = \frac{\tau_0 - \tau_r}{\tau_p - \tau_r} = \frac{\tau_0 - \sigma'_n \mu_d}{\sigma'_n (\mu_s - \mu_d)} \quad (3)$$

directly related to the strength excess S (Andrews, 1976; Viesca & Rice, 2012; Mosconi et al., 2025) by $R = 1/(1 + S)$, is a key nondimensional parameter quantifying the local stress state relative to the static and dynamic fault strength (Ulrich et al., 2019). As a consequence of fault roughness, R can vary significantly across the fault plane (Figure 1d), allowing different portions of the fault to locally approach distinct rupture regimes.

2.4 Von Kármán Characterization of Rupture Heterogeneity

To quantify the spatial organization of rupture heterogeneity, we analyze the rupture velocity fields obtained from the dynamic rupture simulations using a stochastic description based on the von Kármán model. This model has been widely employed to characterize spatial heterogeneity in natural systems because it combines finite correlation lengths with self-affine scaling at short wavelengths (Holliger & Levander, 1992; Mai & Beroza, 2002). Following the framework of Mai and Beroza (2002), we characterize the spatial variability of rupture velocity through its power spectral density (PSD). Whereas the original formulation considers anisotropic spatial statistics with independent along-strike and down-dip correlation lengths, here we adopt an isotropic representation. The two-dimensional power spectral density is computed from the rupture velocity field and subsequently azimuthally averaged to obtain the isotropic one-dimensional spectrum $P(k)$. The resulting spectrum is fitted using the isotropic von Kármán model,

$$P(k) = \frac{C}{(1 + a^2 k^2)^{H+1}}, \quad (4)$$

where $k = \sqrt{k_x^2 + k_z^2}$ is the spatial wavenumber, C is a scaling constant, a is the characteristic correlation length, and H is the Hurst exponent controlling the spectral decay at high wavenumbers thus the contribution of short-wavelength heterogeneity.

Prior to the spectral analysis, a spatial taper is applied to minimize edge effects. For self-arresting ruptures, the taper is applied outside the ruptured area, whereas for runaway ruptures it is applied only near the fault boundaries. In all cases, the prescribed nucleation region is excluded from the analysis to avoid the artificial rupture initiation. The parameters a and H are estimated by nonlinear least-squares regression performed in logarithmic spectral space. To retain only statistically reliable estimates, we discard fits for which the relative uncertainty of either fitted parameter exceeds 50%. This filtering primarily removes poorly constrained spectra associated with ruptures that arrest shortly after nucleation.

3 Results

3.1 Rupture Characteristics

3.1.1 Role of the Roughness Wavelengths

When investigating the effects of 3D fault geometric complexity, one of the key parameters characterizing fault roughness is the wavelength of its spatial fluctuations. The range of wavelengths over which fault geometry varies also controls the length scales over which stress can vary along the fault (Romanet et al., 2020). To assess the role of geometrical heterogeneity on rupture dynamics, we systematically vary the maximum roughness wavelength, $\lambda_{\max}$, thereby isolating the relative contribution of short- and long-wavelength fault geometry. We note that increasing $\lambda_{\max}$ while holding α constant does not simply append longer wavelengths; instead, it redistributes absolute geometric amplitudes across

the entire spectrum. Because the root-mean-square roughness height (h_{rms}) of a fractal model is governed by the longest wavelengths, accommodating these large-scale topographic contributions without violating the fixed α constraint necessitates a systematic reduction in the absolute amplitudes of pre-existing shorter wavelengths.

Figure 2 illustrates the effect of λ_{max} on rupture dynamics through two representative simulations with $\mu_d = 0.19$ and $\alpha = 0.008$. Both models produce self-arresting ruptures, i.e., rupture that spontaneously arrest within the fault boundaries, with comparable final rupture areas of $\sim 1,360$ and $\sim 1,490 \text{ m}^2$, for $\lambda_{\text{max}} = 20$ and 40 m , respectively (Figure 2a-b). Despite their similar rupture extent, the two models exhibit markedly different rupture-speed patterns. The $\lambda_{\text{max}} = 20 \text{ m}$ simulation contains only localized regions of elevated rupture velocity, whereas the $\lambda_{\text{max}} = 40 \text{ m}$ case develops broader high- v_r patches, suggesting that larger-wavelength features may help stabilizing the rupture within a high-velocity regime.

To quantify differences in rupture characteristics, we compute rupture-area-weighted averages of slip, rupture velocity, and stress drop:

$$\bar{\delta} = \frac{\int_{\Sigma} \delta \, dS}{A}; \quad \bar{v}_r = \frac{\int_{\Sigma} v_r \, dS}{A}; \quad \overline{\Delta\tau_d} = \frac{\int_{\Sigma} \Delta\tau_d \, dS}{A} \quad (5)$$

The two models exhibit comparable average slip and stress-drop values, with $\bar{\delta} = 3.3$ and 3.7 mm for $\lambda_{\text{max}} = 20$ and 40 m , respectively, and $\overline{\Delta\tau} = 2.5 \text{ MPa}$ in both cases. In contrast, the model with $\lambda_{\text{max}} = 20 \text{ m}$ shows a lower $\bar{v}_r$ of $0.22v_s$ compared with $0.38v_s$ for $\lambda_{\text{max}} = 40 \text{ m}$.

Further insight into these differences is obtained by characterizing the rupture velocity field using the von Kármán model (see Section 2.4). The power spectral density (PSD) analysis confirms that increasing λ_{max} systematically increases the correlation length (a_c) from 8.2 to 16 m (Figure 2c). This increase reflects the emergence of progressively larger coherent regions of rupture propagation and indicates that rupture-speed variations become correlated over longer spatial scales. Moreover, as evident from Figure 2a–b, the amplitude of v_r fluctuations differs between models, consistent with differences in the long-wavelength spectral intensity of the PSD (Figure 2c). Introducing longer wavelengths in the fault geometry allows rupture speed to vary over broader spatial scales and suggests that an increasing fraction of the rupture speed is concentrated at long spatial wavelengths.

The spatial dependence of rupture speed on λ_{max} is also visible in Figure 2d–e, which show along-dip sections (mode II) representative of the main features of a dip-slip fault. For both $\lambda_{\text{max}} = 20$ and 40 m , change in rupture speed (black line) broadly tracks the spatial variations of the R parameter (orange line) highlighting the strong control exerted by local stress conditions on rupture-front propagation. However, clear differences emerge in the spatial evolution of v_r . For $\lambda_{\text{max}} = 20 \text{ m}$, short-wavelength variations of the R parameter control rapid and intermittent rupture-front acceleration and deceleration (Figure 2d), explaining the absence of large-scale spatial correlation ($a_c = 8.2 \text{ m}$) in the PSD of v_r . High-to-low rupture-speed variations are coupled with local fluctuations in the slip-velocity field (Figure 2f), resulting in a non-axisymmetric and temporally discontinuous rupture propagation. The peak slip rate exhibits pronounced spatial variability, as does the asymptotic slip velocity in the rupture tail. The resulting propagation alternates between pulse-like behavior, particularly during the arrest phase, and crack-like propagation near the injection point, where σ'_n is reduced. In contrast, the model with surface roughness limited to $\lambda_{\text{max}} = 40 \text{ m}$ shows an R parameter varying over larger spatial scales, allowing rupture speed to fluctuate over longer wavelengths (Figure 2e). The higher spatial correlation length of v_r ($a_c = 16 \text{ m}$) is associated with a smoother evolution of the slip-rate field $\dot{\delta}$ (Figure 2g), reflecting a more coherent rupture front able to accelerate over a large portion of the fault before undergoing an extended decelera-

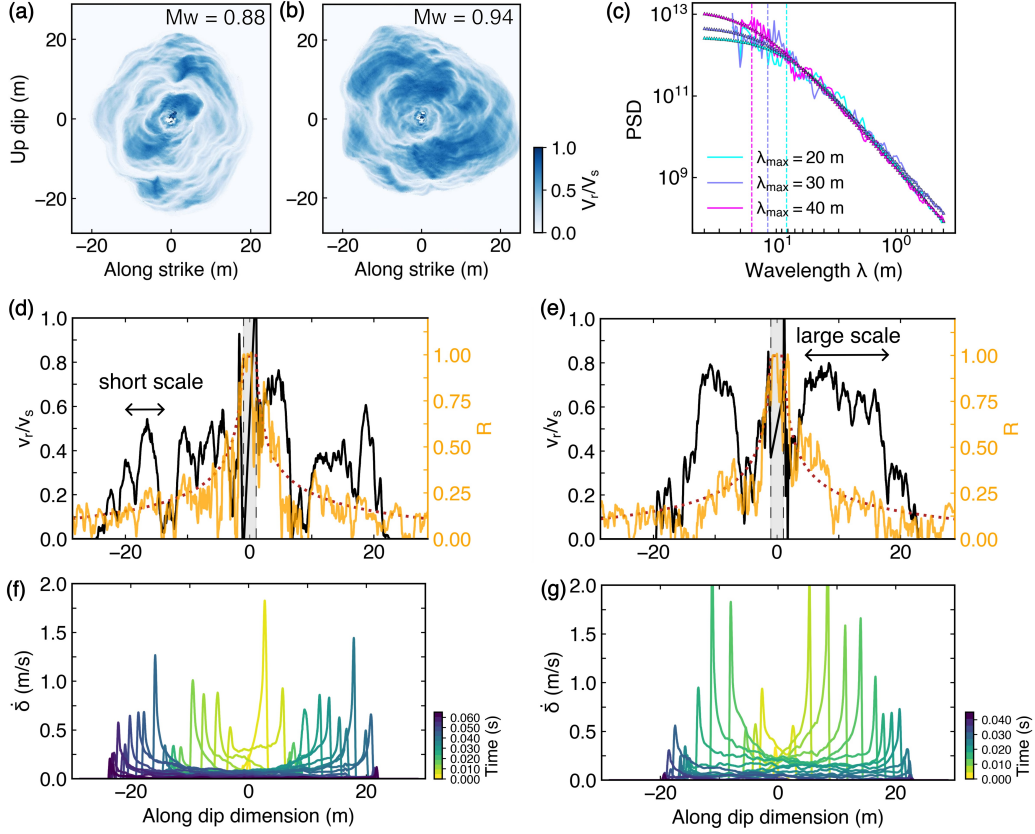


Figure 2. Rupture behavior under different maximum roughness wavelengths $\lambda_{\max}$ with $\mu_d = 0.19$ and $\alpha = 0.008$. **a-b)** Rupture velocity distributions for 3D rough faults with $\lambda_{\max} = 20$ and 40 m, respectively. **c)** Two-dimensional power spectral density (PSD) of the rupture speed for models with roughness $\lambda_{\max} = 20, 30$, and 40 m. Vertical lines show the correlation length. **d-e)** Along-dip profiles of rupture speed (black line) and relative prestress ratio R (orange line) for models with roughness $\lambda_{\max} = 20$ and 40 m. The dashed red line represents R for a planar fault. **f-g)** Spatio-temporal evolution of slip rate sampled at 0.005 s intervals, along an along-dip fault profile for models with $\lambda_{\max} = 20$ and 40 m. These simulations correspond with self-arresting ruptures.

tion phase. The evolution of $\dot{\delta}$ predominantly indicates crack-like propagation (Kostrov, 1964).

In addition to the local spatial heterogeneity introduced by the surface roughness, the spatial distribution of the R parameter is affected by the pore-pressure perturbations induced by fluid injection. Following eq. 3, R decreases spatially from the injection point toward the fault edges. In planar fault models, this imposed gradient leads to a progressive reduction of v_r and ultimately to rupture arrest (Mosconi et al., 2025), producing self-arresting ruptures without invoking additional barriers or heterogeneity. When fault roughness is included, under the same frictional conditions ($\mu_d = 0.19$), both $\lambda_{\max} = 20$ and 40 m models exhibit an overall spatial decay of rupture speed, despite localized phases of acceleration and deceleration. This behavior remains characteristic of self-arresting rupture fronts, particularly in the case of $\lambda_{\max} = 20$ m.

3.1.2 Role of Roughness Amplitude

In this section, we investigate how the roughness amplitude (α) influences the dynamics of fluid-induced ruptures. Increasing α enhances the additional shear resistance generated by fault topography, commonly referred to as roughness drag, which acts to inhibit rupture propagation. For a two-dimensional rough fault, this additional resistance can be approximated as (Fang & Dunham, 2013):

$$\tau_{drag}^{2D} \approx \frac{8\pi\alpha^2 G^* \bar{\delta}}{\lambda_{min}} \quad (6)$$

with, $G^* = G/(1 - \nu)$ and G the shear modulus. Roughness drag scales with α^2 and the average fault slip, implying that rougher fault surfaces require higher τ_0 to sustain ruptures of comparable size. Following Taufiqurrahman et al. (2022) we can use the approximation $\tau_{drag}^{3D} = C \tau_{drag}^{2D}$, where C is a non-dimensional constant of ~ 0.4 , to estimate the roughness drag for a 3D rough fault geometry. For our models, $\tau_{drag}^{3D} = 0.46$ MPa for $\alpha = 0.008$, whereas $\tau_{drag}^{3D} = 0.13$ MPa for $\alpha = 0.004$. Consistent with this increase, doubling the roughness amplitude changes the rupture regime from a continuous rupture ($A = 2684 \text{ m}^2$) to a self-arresting rupture ($A = 1033 \text{ m}^2$) under otherwise identical frictional ($\mu_d = 0.19$) and stress conditions (Figure 3a-b). This behavior agrees with previous numerical studies highlighting the inhibiting effect of roughness drag on rupture propagation (Fang & Dunham, 2013; Bruhat et al., 2020; Maurer et al., 2020; Taufiqurrahman et al., 2022).

The simulation with $\alpha = 0.008$, uses the same parameters as the $\lambda_{max} = 20$ simulation presented in Section 3.1.1, differing only in the realization of the rough fault surface. As expected, the rupture displays similar characteristics, including large-amplitude and intermittent acceleration and deceleration of the rupture front (Figure 3d), ultimately leading to a confined, self-arresting rupture. The slip-velocity field shows a pronounced unidirectional downwards pulse, with high peak slip rates and non-constant values in the rupture tail. Near rupture arrest, high slip velocities persist locally at the rupture front, while the center of the fault exhibits much smaller values.

A lower α value under the same intermediate dynamic friction ($\mu_d = 0.19$) leads to a rupture that propagates across nearly the entire fault (Figure 3b). In this case, the smoother fault geometry leads to a more spatially coherent distribution of the R parameter (orange line in Figure 3e), and rupture speed exhibits a less heterogeneous and more spatially smoothed pattern (Figure 3b-e). Accordingly, the slip velocity remains non-zero at the center of the crack, indicating predominantly crack-like propagation, and displays lower peak values compared to the higher-roughness case (Figure 3g versus Figure 3f).

Using the more quantitative characterization of v_r based on the von Kármán model, we further observe that increasing the roughness amplitude α systematically elevates the spectral power of the rupture velocity across all wavenumbers (Figure 3c). In contrast, the correlation length a_c varies only weakly with α , showing at most a decrease for the rougher fault realization (vertical dashed lines in 3c).

3.1.3 Effect of Residual Friction

During dynamic rupture propagation, the residual stress left behind the rupture front, equal to $\sigma'_n \mu_d$ for a linear slip-weakening law, controls the dynamic stress drop $\Delta\tau_d$ (Barras et al., 2019). Within the framework of classical fracture mechanics (Freund, 1998), the crack-tip stress intensity factor, $K_0 \sim \Delta\tau_d \sqrt{\mathcal{L}}$, where $\mathcal{L}$ is the crack length, governs crack propagation. Consequently, understanding how $\Delta\tau_d$ influences the rupture dynamics of fluid-induced earthquakes on rough faults is key to constraining their mechanics, particularly how spatial heterogeneity in $\Delta\tau_d$ affects rupture-front dynamics.

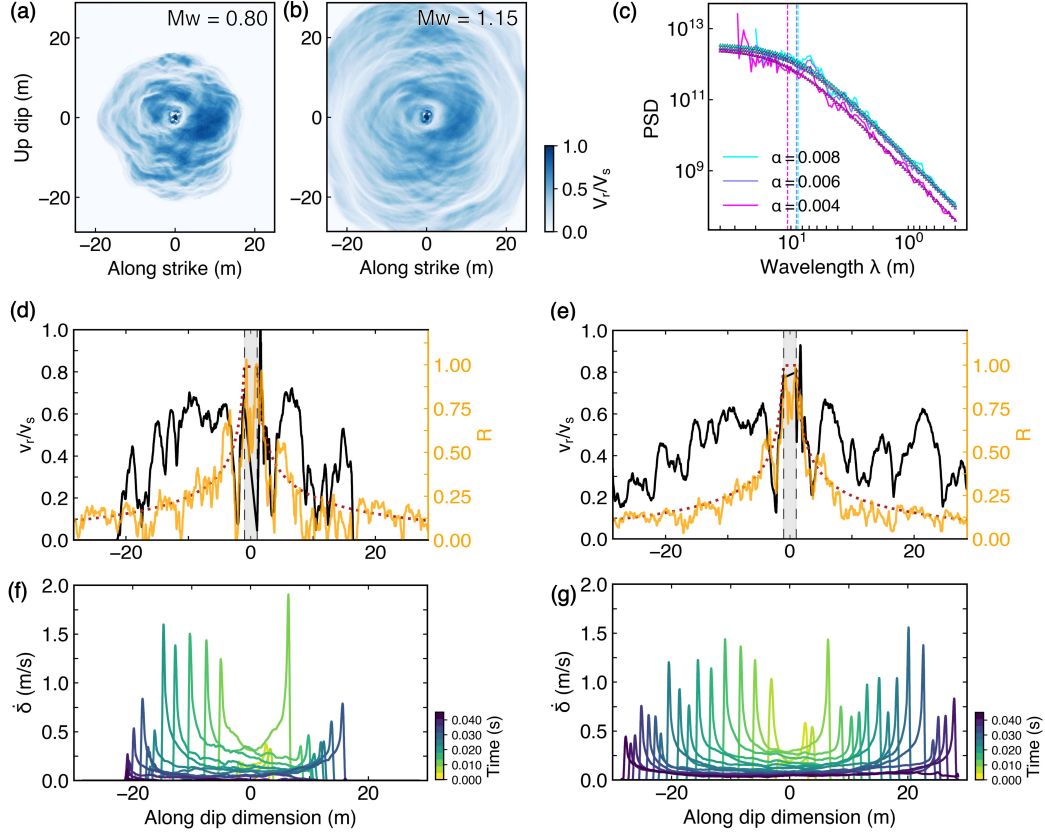


Figure 3. Rupture behavior under different roughness amplitude α with $\mu_d = 0.19$ and $\lambda_{max} = 20$ m. a-b) Rupture velocity distributions for 3D rough faults with $\alpha = 0.008$ and 0.004 , respectively. **c)** Two-dimensional power spectral density (PSD) of the rupture speed for models with roughness $\alpha = 0.004$, 0.006 , and 0.008 . Vertical lines show the correlation length. **d-e)** Along-dip profiles of rupture speed (black line) and relative prestress ratio R (orange line) for models with roughness $\alpha = 0.008$ and 0.004 . The dashed red line represents R for a planar fault. **f-g)** Spatio-temporal evolution of slip rate sampled at 0.005 s intervals, along an along-dip fault profile for models with $\alpha = 0.008$ and 0.004 .

In this section, we therefore investigate this effect by systematically varying μ_d to achieve different values of $\Delta\tau_d$ (Mosconi et al., 2025).

A first-order effect of decreasing μ_d from 0.20 to 0.17 is to govern the transition from self-arresting to run-away ruptures (Figure 4a–b). This transition can be understood either in terms of the R parameter, whose absolute value increases, or through the fracture-mechanics crack-tip energy balance (Freund, 1998). Previous studies have shown that, for fluid-induced ruptures under the small-scale yielding approximation, Linear Elastic Fracture Mechanics (LEFM) can predict the final rupture size (Garagash & Germanovich, 2012; Sáez & Lecampion, 2024; Galis et al., 2017; Ciardo & Rinaldi, 2022; Mosconi et al., 2025), capturing the transition from self-arresting to run-away behavior as μ_d decreases.

This transition is accompanied by a marked change in the spatial evolution of v_r (Figure 4d–e). Self-arresting ruptures exhibit an acceleration near the nucleation patch (just outside the nucleation region), where R is larger, followed by a progressive spatial

decrease in v_r as R decreases. As shown in Figure 4d for the mode II direction, the rupture tip, after repeated phases of acceleration and deceleration, ultimately arrests in a region where R is lower than the reference value for the planar fault (dashed orange line in Figure 4d). In contrast, the continuously propagating rupture (Figure 4e) shows the same initial acceleration in the reduced σ'_n region (injection point), but the rupture speed does not progressively decrease. When the rupture front encounters the same low- R region that arrested the rupture in the $\mu_d = 0.20$ case, it only undergoes a modest deceleration. The higher available driving force allows the rupture front to overcome the barrier and propagate across the entire fault. Therefore, for reduced μ_d , neither the stress gradient nor the roughness-induced heterogeneity are sufficient to arrest the rupture.

The contrasting v_r distributions also reflect significant differences in the spatio-temporal evolution of slip velocity (Figure 4f–g), similarly to the behavior observed for the roughness parameters explored in Sections 3.1.1 and 3.1.2. For $\mu_d = 0.20$, the propagation transitions to a predominantly pulse-like mode. This pulse-like nature, combined with a net deceleration phase, amplifies the front’s sensitivity to local roughness, inducing the observed high-frequency fluctuations in v_r . In this case, local roughness-induced heterogeneity strongly influence the evolution of the peak slip rate at the rupture front, which appears spatially fragmented and evolves independently on the opposite sides of the rupture (Figure 4f). Reducing μ_d to 0.17 leads, consistently with the behavior of v_r , to higher peak slip rates (Figure 4g). However, the overall slip-rate evolution indicates that under a continuously propagating rupture front it predominantly follows a crack-like propagation mode. In this case, the slip rate in the crack tail remains nearly constant, allowing the entire rupture length to remain dynamically interacting, even though the peak slip rate at the rupture front continues to exhibit local variability.

Analyzing the spatial autocorrelation of the v_r fields shows a net increase in a_c decreasing μ_d values (Figure 4c). This observation could be related to the sensitivity of a_c to the rupture dimension (Mai & Beroza, 2002); in fact, while $A \sim 285 \text{ m}^2$ for $\mu_d = 0.20$, it reaches $A \sim 2347 \text{ m}^2$ for $\mu_d = 0.17$. Alternatively, this behavior may stem from the reduced sensitivity of the rupture front to roughness-induced heterogeneity in cases of a larger dynamic stress drop (e.g., lower μ_d). Furthermore, the PSD amplitude increases with decreasing μ_d , which is consistent not only with higher rupture velocities but also with larger rupture areas that contribute to higher spectral amplitudes at long wavelengths.

3.2 Overall Statistical Properties

3.2.1 Micro-earthquakes Magnitude

The distribution of the final magnitude for our 3D dynamic rupture models of fluid-induced micro-earthquakes is shown in Figure 5. A first observation common to all explored parameter sets, both in terms of roughness and frictional properties, is the distinct bimodality of the M_w probability density functions (PDF), with the two peaks which correspond to two different rupture behaviors.

The first peak occurs at approximately $M_w \sim -1$ and represents ruptures that remain almost entirely confined within the overstressed region of the nucleation patch. These events therefore correspond to failed nucleation. To verify this physical mechanism, we can establish a theoretical baseline using the circular crack relation $M_0 = \frac{16}{7} \Delta\tau_d \mathcal{L}^3$ (Eshelby, 1957). By setting $\mathcal{L}$ to the radius of the overstressed region and considering the imposed overstress at the nucleation point (Section 2.2), we estimate a magnitude of $M_w \sim -1.2$, consistent with the $M_w \sim -1$ observed. The spread observed in the PDF, for this first peak, arises because ruptures are not always strictly confined within the $\sim 1 \text{ m}$ overstressed region; in some cases they decelerate beyond it (Galis et al., 2017), producing slightly larger rupture radii.

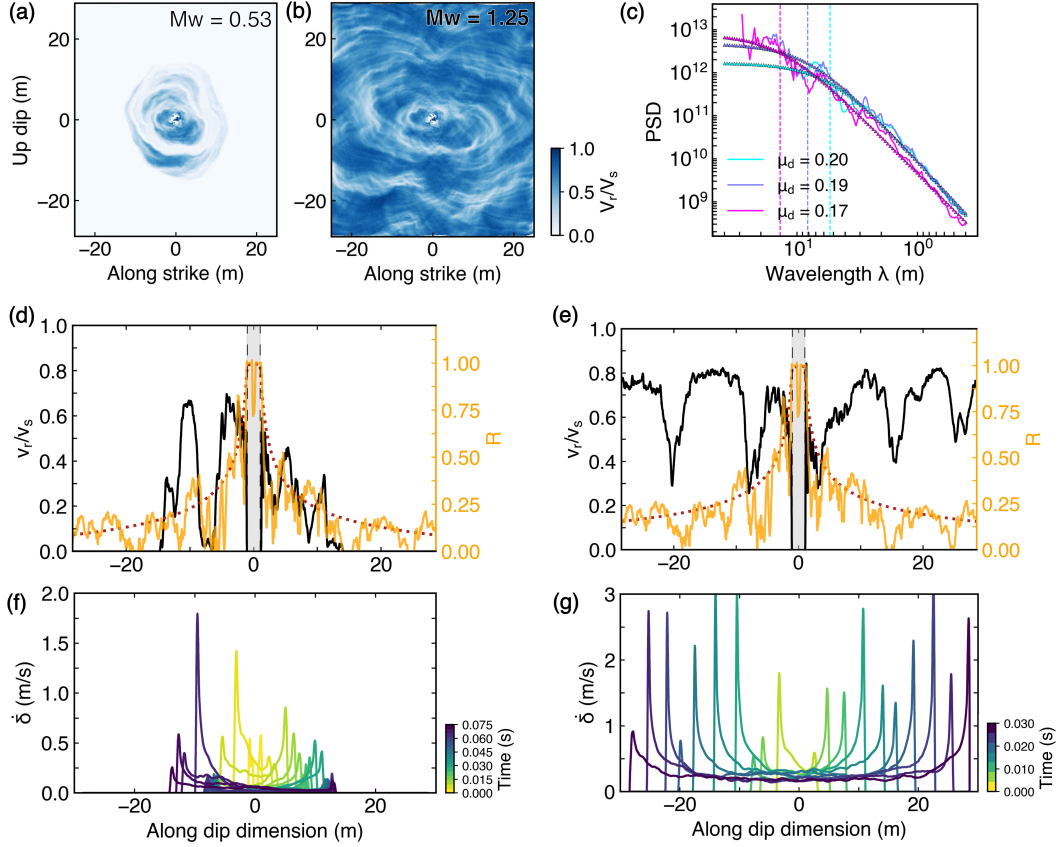


Figure 4. Rupture behavior under different dynamic friction μ_d with $\lambda_{max} = 20$ m and $\alpha = 0.008$. **a-b)** Rupture velocity distributions for 3D rough faults with $\mu_d = 0.20$ and 0.17 , respectively. **c)** Two-dimensional power spectral density (PSD) of the rupture speed for models with roughness $\mu_d = 0.20, 0.19$ and 0.17 . Vertical lines show the correlation length. **d-e).** Along-dip profiles of rupture speed (black line) and relative prestress ratio R (orange line) for models with roughness $\mu_d = 0.20$ and 0.17 . The dashed red line represents R for a planar fault. **f-g)** Spatio-temporal evolution of slip rate sampled at 0.005 s intervals, along an along-dip fault profile for models with $\mu_d = 0.20$ and 0.17 .

The second peak is instead showing the most probable rupture magnitude for events that achieve sustained dynamic propagation past the nucleation zone. The M_w of this second peak exhibits a systematic dependence on both the fault properties in terms of roughness and frictional parameters (Figure 5).

Comparing the M_w PDFs for different values of μ_d (0.20, 0.19, 0.17) shows that the maximum observed M_w progressively increases as μ_d decreases. This trend is consistent across all explored values of α and λ_{max} (Figure 5a-d-g, b-e-h, c-f-i). In addition, the M_w PDFs for lower μ_d are depleted in intermediate M_w range separating the two primary peaks. However, the degree of flattening of the PDFs in the intermediate M_w range also depends on the roughness amplitude α . For the higher residual friction ($\mu_d = 0.20$) (Figure 5a-b-c), a relatively broad distribution of M_w is observed for all α , with events spanning the range between the two primary peaks. This behavior changes for $\mu_d = 0.19$, where intermediate-magnitude events are mainly observed for the largest α , whereas for smaller α values the distribution shows a clearer separation between failed

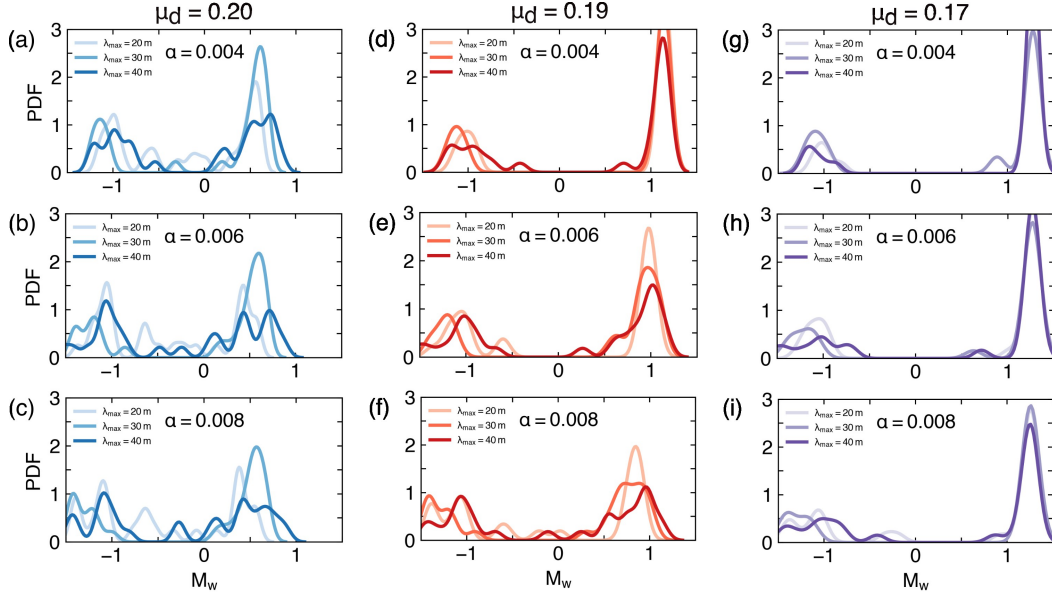


Figure 5. Distribution of moment magnitudes (M_w) of the simulated rupture models as a function of roughness and dynamic friction parameter. For each column, panels from top to bottom correspond to roughness amplitudes $\alpha = 0.004, 0.006$, and 0.008 , respectively. Individual curves within each panel are color-coded by the maximum wavelength $\lambda_{\max}$. **a-b-c)** M_w distributions for $\mu_d = 0.20$. **d-e-f)** M_w distribution for $\mu_d = 0.19$. **g-h-i)** M_w distribution for $\mu_d = 0.17$.

nucleation and fully developed instabilities (Figure 5d–e–f). This separation becomes even more pronounced for the lower friction value $\mu_d = 0.17$. In this case, across all explored α values, roughness amplitude does not significantly affect either the minimum or maximum characteristic M_w . Instead, the distribution exhibits a clear dichotomy between the two rupture behaviors, with essentially no intermediate magnitudes observed.

The maximum expected M_w exhibits a complex sensitivity to the maximum roughness wavelength $\lambda_{\max}$ and amplitude α . Under conditions where the M_w distribution is complex and not restricted to the two main peaks, increasing $\lambda_{\max}$ generally increases the probability of larger fluid-induced earthquake magnitudes (e.g., Figure 5a–c). This trend remains valid until either the roughness amplitude decreases or μ_d is reduced, both of which tend to flatten the intermediate portion of the M_w distribution. For the largest magnitudes, it is noticeable that for low μ_d (0.19, 0.17) and low α (0.004 and 0.006) the rupture size is largely insensitive to variations in $\lambda_{\max}$. In contrast, when $\mu_d = 0.19$ for a large roughness amplitude ($\alpha = 0.008$), the maximum expected M_w increases with $\lambda_{\max}$ (Figure 5f). At the same time, the maximum likelihood of the final fluid-induced earthquake size strongly depends on α (Maurer et al., 2020). Dynamic perturbations introduced by fault roughness during rupture propagation generate an additional shear resistance to slip (τ_{drag} , Equation 6). Therefore, for a fixed initial shear stress, increasing α is expected to reduce the final rupture size. If instead the roughness parameters are fixed, the final M_w also depends on the imposed μ_d .

3.2.2 Spatial Random Fields Parameters

A quantitative approach to describe the complexity of rupture kinematics is to characterize the spatial random field properties of the rupture parameters using their 2D av-

eraged spectral content (Mai & Beroza, 2002). In this section, we analyze the rupture-speed (v_r) maps obtained from all 3D dynamic rupture simulations of fluid-induced micro-earthquakes using the von Kármán model described in Section 2.4.

A first clear observation is the effect of decreasing μ_d . As μ_d decreases, ruptures become larger and more prone to run-away behavior, with higher rupture speeds. Crucially, the rupture also experiences a broader range of absolute speeds. Correspondingly, the amplitude of the 2D averaged PSD increases as μ_d decreases (Figure 6a–d–g). In addition, decreasing μ_d leads to an increase in the correlation length a_c (Figure 6b–e–h). This effect may be controlled by the larger rupture dimensions associated with lower μ_d (as discussed in Section 3.1.3), or by a reduced influence of fault roughness when the dynamic stress drop $\Delta\tau_d$ is larger. Overall, these results indicate that decreasing μ_d tends to produce a less heterogeneous spatial distribution of v_r . The Hurst exponent remains broadly stable near $H \sim 0.5$ for both $\mu_d = 0.20$ and 0.19 . For $\mu_d = 0.17$, however, H decreases. This flatter high-wavenumber spectral slope indicates that short-wavelength heterogeneity becomes more pronounced relative to the long-wavelength background as dynamic friction drops (Figure 6c–f–i).

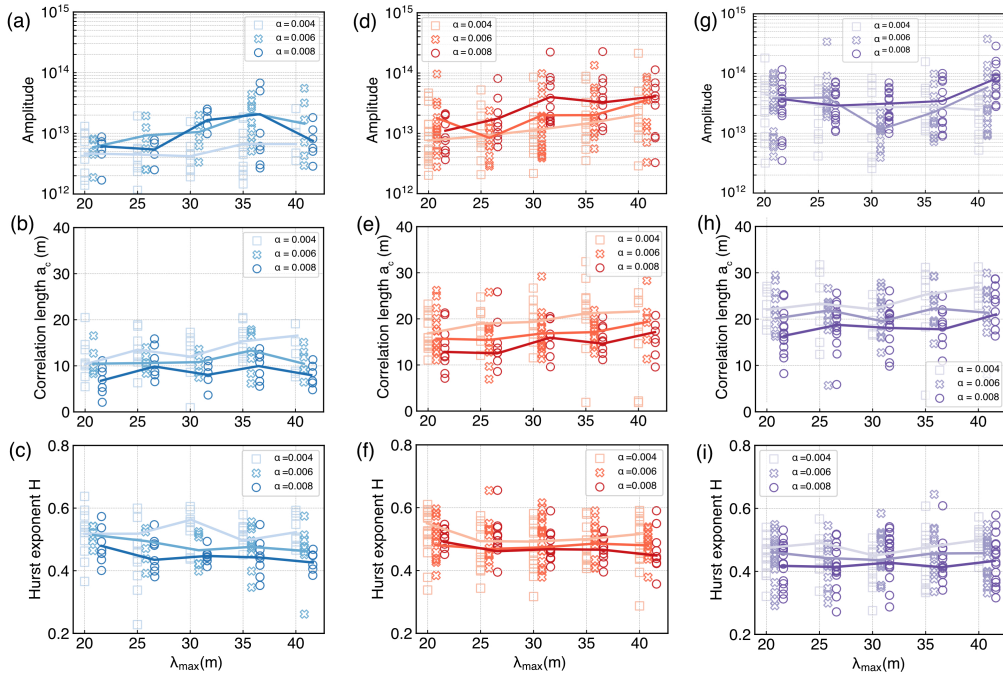


Figure 6. Spatial random-field parameters of rupture front speed. **a–c)** Long-wavelength spectral amplitude, correlation length (a_c), and Hurst exponent (H), respectively, for models with $\mu_d = 0.20$. **d–f)** Same as (a–c) for $\mu_d = 0.19$. **g–i)** Same as (a–c) for $\mu_d = 0.17$. All quantities are plotted as a function of $\lambda_{\max}$, with the marker shapes indicating the roughness amplitude (α). Solid lines shows the average value of each parameter for different wavelengths.

The second important factor controlling the spatial evolution of v_r is $\lambda_{\max}$. For all values of μ_d , increasing $\lambda_{\max}$ generally leads to a larger amplitude of the v_r PSD (with the exception of intermediate $\lambda_{\max}$ for $\mu_d = 0.17$), as shown in Figure 6a–d–g. Increasing $\lambda_{\max}$ also results in larger correlation lengths a_c , indicating that larger roughness wavelengths promote larger-scale heterogeneity and a comparatively smoother spatial distribution.

bution of v_r . Within each class of μ_d , however, no clear dependence of the exponent H on $\lambda_{\max}$ can be identified.

Finally, we consider the effect of roughness amplitude α on the spatial distribution of v_r . For the higher friction case ($\mu_d = 0.20$), the influence of α on both the PSD amplitude and a_c is difficult to generalize because of the large scatter in the results (Figure 6a-b). In contrast, for $\mu_d = 0.19$, α correlates with both amplitude and a_c : increasing roughness amplitude leads to larger perturbation amplitudes while simultaneously reducing the correlation length a_c (Figure 6d-e). A similar trend in a_c is also observed for the lower friction case $\mu_d = 0.17$. These results suggest that increasing fault roughness amplitude leads to smaller characteristic spatial scales of heterogeneity in v_r (Figure 6h).

The exponent H (Figure 6c-f-h) is also sensitive to the roughness amplitude for all μ_d . In particular, H appears to be anti-correlated with α , indicating that increasing roughness amplitude enhances the contribution of short-wavelength components in the v_r distribution. This observation is consistent with the findings of Bruhat et al. (2020), who reported a similar anti-correlation between H and α in the slip distributions of 2D dynamic rupture models of large natural earthquakes.

4 Discussion

4.1 Heterogeneous Rupture Front Loads

Assessing the maximum magnitude of fluid-induced earthquakes first requires understanding the mechanisms controlling rupture arrest and the energy available to sustain rupture propagation.

At large scales, induced earthquakes are characterized by a gradient in the effective normal stress, σ'_n (Figure 1c-d). This gradient, superimposed on the natural stress heterogeneity produced by 3D fault geometric irregularities, can lead to an interplay between these two factors (i.e., spatially variable effective normal stress and initial stress) in controlling rupture arrest. In our case, because rupture nucleates at the center of the pressurized patch, nucleation occurs in a region of relatively low fracture toughness K_c , which quantifies the fault's resistance to crack propagation (Galis et al., 2017; Sáez & Lecampion, 2024). Expressed in terms of fracture energy, this corresponds to $G_c = K_c^2/2\mu$. Moving away from the injection point, the spatial increase in σ'_n leads to a corresponding increase in K_c (red lines in Figure 7). The dominant control between these competing factors depends on both fault roughness and frictional properties. To evaluate which of these competing effects controls rupture propagation, we compare the crack-tip loading with the local fracture resistance using the Irwin criterion. According to this criterion, rupture propagation occurs when the crack-tip static stress intensity factor (SIF), K_0 reaches the fracture toughness, or critical stress intensity factor, K_c (details on the computation of K_0 and K_c are provided in the Supplementary Material). Under the heterogeneous rupture conditions considered here (Figure 2a-b, Figure 3a-b, Figure 4a-b), K_0 , K_c , and v_r all vary spatially along the fault. To account for this variability, we compute these quantities along 1D half-crack, along-dip fault sections within an angular range of $\pm 10^\circ$. The resulting variability is represented in Figure 7 by shaded areas indicating the 5th and 95th percentiles, while the solid lines denote the median values.

The different $\lambda_{\max}$ values control the larger spatial scale over which fault roughness varies. For short wavelengths ($\lambda_{\max} = 20$ m), stress variations maintain a highly localized spatial character, producing relatively small local fluctuations in the load at the crack tip (Figure 7a), thus $K_0 \sim \Delta\tau_d\sqrt{\mathcal{L}}$. For such short-wavelength heterogeneity, the spatial growth of K_0 with crack length is counterbalanced by the spatial increase of K_c . As a result, rupture propagation is primarily controlled by the gradient in σ'_n , which increases with distance from the injection point. This progressive increase in K_c leads

to rupture deceleration and eventual arrest (Figure 7a). In contrast, larger wavelengths ($\lambda_{\max} = 40$ m) imply longer spatial variations in $\Delta\tau_d$, producing extended portions of the rupture where the available load is reduced. In this case, the rupture front can experience a more abrupt arrest rather than a gradual deceleration (Figure 7b). At the same time, large-scale variations in surface roughness can also generate extended fault regions with elevated v_r (Figure 2e), corresponding to locally favorable conditions where $K_0 \gg K_c$ (Figure 7b). The larger spatial extent of these heterogeneity promotes both stronger acceleration and deceleration phases. However, compared to short-wavelength variability, long-wavelength stress heterogeneity is more effective at arresting rupture due to its greater spatial extent along the fault, as the width of the barrier plays a critical role (Molina-Ormazabal et al., 2023).

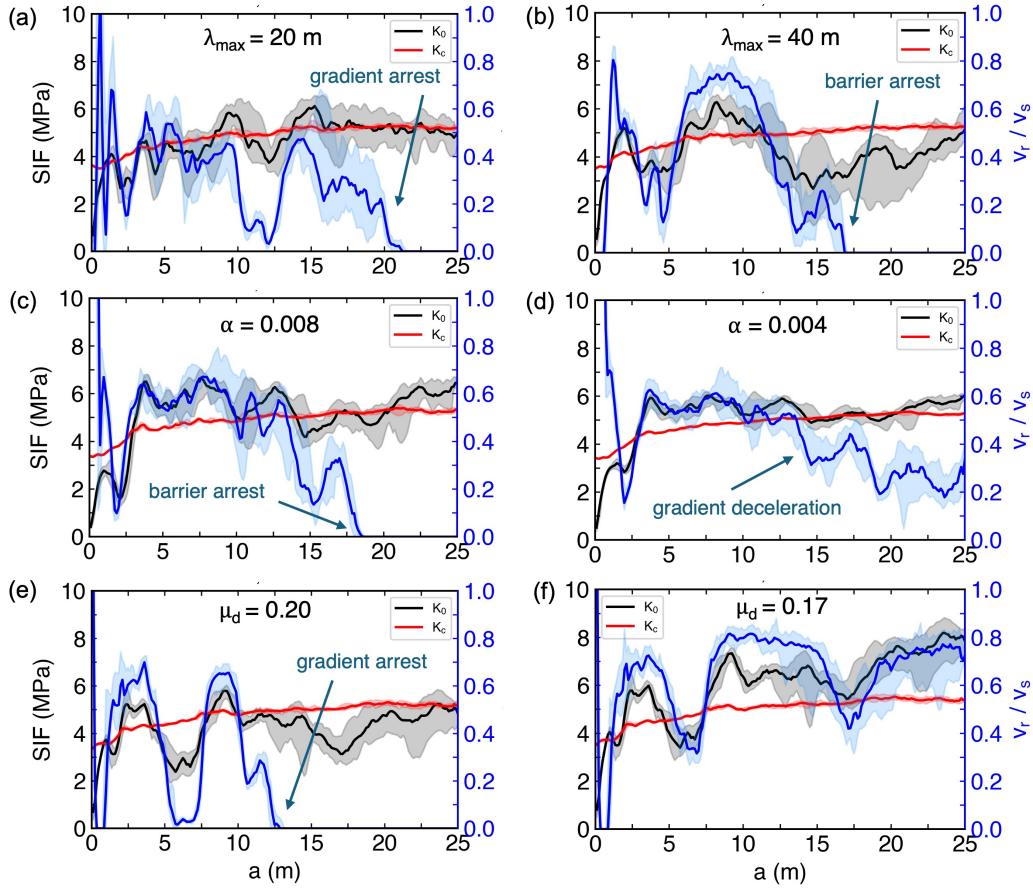


Figure 7. Fracture mechanics rupture tip analysis. a-b) For the model with $\mu_d = 0.19$, $\alpha = 0.008$, and $\lambda_{\max} = 20$ and 40 m, respectively, showing the static stress intensity factor (black), fracture toughness (red), and rupture speed (blue) as a function of half-crack length along a dip-section of the fault. c-d) Same as (a), for $\mu_d = 0.19$, $\lambda_{\max} = 20$ m, and $\alpha = 0.008$ and 0.004, respectively. e-f) Same as (c), for $\lambda_{\max} = 20$ m, $\alpha = 0.008$, and $\mu_d = 0.20$ and 0.17, respectively. Shaded areas represent the 5th–95th percentiles, while solid lines denote median values. Measurements are computed within a $\pm 10^\circ$ window around the along-dip fault direction.

The presence of a rough fault surface inherently introduces heterogeneous loading conditions at the rupture front (Sun & Cattania, 2025). Fault surfaces characterized by different roughness amplitudes α produce perturbations of different amplitudes in K_0

(Figure 7c–d), where large roughness amplitudes ($\alpha = 0.008$) increase the local K_0 leading to higher v_r and large spatial perturbations within the rupture area (Figure 6a–d–g). However, increasing α also enlarges regions with low K_0 , which act as potential barriers and play an important role in rupture arrest and barrier efficiency (Fryer et al., 2024). This effect is further illustrated by the rupture behavior for $\alpha = 0.004$. In this case, the smaller perturbations in K_0 produce only limited variations in v_r (Figure 7d). At locations where the model with $\alpha = 0.008$ exhibits an almost complete rupture arrest (Figure 7c), the rupture front for $\alpha = 0.004$ only slows down and continues propagating. In the second case, rupture speed decreases progressively due to the spatial increase in K_c , but the rupture ultimately propagates across the entire fault plane.

Increasing the roughness amplitude does not simply enhance rupture acceleration. Instead, it amplifies the stress heterogeneity at the rupture front, creating both extended regions highly favorable to rupture propagation and equally extensive regions that strongly inhibit it. Although the rupture may locally accelerate within favorable patches, its ultimate survivability is governed by the unfavorable regions, characterized by low K_0 and low R , which drive crack-tip deceleration and arrest. By contrast, smaller roughness amplitudes generate a smoother stress, allowing the rupture front to propagate more steadily under the large-scale stress gradient imposed by σ'_n .

A different fault response emerges when varying μ_d , which directly controls the energy balance at the rupture front. For higher μ_d (0.20), the rupture exhibits significant variability in v_r , driven by local fluctuations in K_0 (Figure 7e). In this case, rupture arrest occurs primarily because $K_0 < K_c$ ahead of $\mathcal{L}$ approximately 10 m. Although local peaks in v_r are associated with local increases in K_0 , the overall growth of $K_0 \propto \mathcal{L}$ is counterbalanced by the spatial increase in K_c . As a result, rupture propagation is ultimately inhibited by the gradient in effective normal stress induced by pore-pressure variations. In contrast, decreasing μ_d to 0.17 produces an overall upward shift in K_0 toward higher values. Despite a similar spatial growth of K_c , the higher absolute level of K_0 allows the rupture front to propagate across the entire fault at relatively high rupture speeds. Even in regions where $K_0 < K_c$, the rupture front only undergoes local deceleration rather than arrest, indicating that the rupture can overcome local barriers through inertial effects and sustain propagation (Albertini et al., 2021).

We emphasize the limitations of the approach adopted to interpret the driving forces of fluid-induced micro-earthquakes on rough faults. Owing to the high degree of stress heterogeneity, rupture shapes generally deviate from circular geometries (which are only expected for $\nu = 0$), instead developing elongated, elliptical shapes with a preferential extension in the Mode II direction. Moreover, heterogeneous fault conditions lead to highly irregular rupture growth, further deviating from the assumptions underlying classical linear elastic fracture mechanics (LEFM). In addition, under such complex conditions, some ruptures exhibit pulse-like propagation, departing from the crack-like behavior typically resulting from LEFM. This requires modified approaches to properly evaluate the energy flux at the crack tip (Nielsen & Madariaga, 2003). Despite these limitations, LEFM remains a powerful framework to describe the loading conditions at the rupture front and, to some extent, provides results consistent with dynamic rupture simulations on rough faults. This apparent agreement likely arises because, despite the complexity of the rupture process, the use of a linear slip-weakening law –representing a simplified description of dynamic weakening (Cocco et al., 2023)– results in a well-defined fracture energy G_c (Brener & Bouchbinder, 2021; Kammer et al., 2024), even under strongly heterogeneous conditions, and ensures that energy dissipation remains strongly localized at the rupture front.

4.2 Connecting Magnitude Distributions to Fracture Mechanics

In Section 4.1, we discuss how the heterogeneous loading at the rupture front, induced by fault roughness, controls rupture dynamics. Here, we examine how these effects translate into the statistical properties of the resulting micro-earthquake magnitudes.

We have shown that λ_{max} controls the spatial scale of heterogeneity (Figure 2). Accordingly, larger λ_{max} promotes larger magnitudes when roughness-induced heterogeneity is dynamically important (e.g. large roughness amplitude α) and K_0 is comparable to K_c (high and intermediate μ_d). In these cases, the spatial organization of roughness, particularly its characteristic scale, directly influences rupture propagation. Larger λ_{max} increases the spatial extent over which large $\Delta\tau_d$ can develop, promoting larger M_w events. In contrast, for low α , the influence of roughness is reduced. Local heterogeneity does not significantly perturb K_0 , and rupture propagation is primarily governed by the large-scale gradient in K_c (Figure 7d). As a result, variations in λ_{max} have a limited impact on the maximum magnitude (Figure 5d–e). On the other hand, variations in α systematically affect the most probable magnitude for all combinations of λ_{max} and μ_d . Consistent with previous studies on fault roughness (Fang & Dunham, 2013; Shi & Day, 2013; Bruhat et al., 2016; Maurer et al., 2020), we find that increasing α leads to smaller rupture sizes, reflected in a decrease of the most probable M_w .

A similar trend is observed when decreasing μ_d . As discussed earlier, lower μ_d increases the absolute value of K_0 , promoting a transition toward runaway rupture behavior. As the ratio K_0/K_c increases, the magnitude distribution becomes simpler, with a progressive suppression of intermediate magnitudes between the two characteristic populations: failed nucleation events and fully developed ruptures (e.g., Figure 5b–e–h). A comparable narrowing of the magnitude spectrum can also arise from the effect of α . When roughness amplitude is sufficiently large, it enhances the variability of rupture sizes, provided that local variations in K_0/K_c do not dominate rupture-front dynamics. In this regime, the interplay between heterogeneity amplitude and fracture mechanics controls the breadth of the observable magnitude distribution.

4.3 Role of the Cohesive-zone Size

The cohesive zone is a key feature of dynamic earthquake rupture, representing the finite region surrounding the rupture front where frictional weakening takes place and slip rates typically reach their highest values (details on cohesive-zone resolution are in the Supplementary Material). The evolution of the cohesive-zone size, Λ , therefore provides additional insight into the complexity of fluid-induced micro-earthquakes and the processes controlling rupture propagation. Following (Day et al., 2005), we define Λ as the portion of the rupture undergoing dynamic weakening. Under a linear slip-weakening constitutive law, this corresponds to the region extending from the first point that reaches the peak stress τ_p to the first point behind the rupture front where slip exceeds the critical slip distance d_c , and the stress has dropped to the residual level τ_r . More importantly, the cohesive-zone size is directly related to the energy budget and therefore reflects the local driving conditions of rupture propagation. Under heterogeneous stress conditions, spatial variations in Λ provide valuable insight into the variability of the crack-driving force at the rupture tip. In classical fracture mechanics, Λ is defined as

$$\Lambda = \Lambda_0 f^{-1}(v_r), \quad \text{with} \quad \Lambda_0 = C \frac{G^* d_c}{\Delta\tau_b}, \quad (7)$$

where Λ_0 is the static cohesive zone size, $\Delta\tau_b = \tau_p - \tau_r$ is the breakdown stress drop, $f^{-1}(v_r)$ is a universal dimensionless function of the rupture velocity that accounts for the Lorentz contraction of the cohesive zone as the rupture velocity approaches the Rayleigh wave speed c_r (i.e., $f^{-1}(v_r) \rightarrow 0$ as $v_r \rightarrow c_r$) (Freund, 1998) and C is a numerical prefactor (Day et al., 2005; Viesca & Garagash, 2018). For a crack propagating under ho-

659 homogeneous stress conditions, the cohesive zone size decreases as $\Lambda \propto \sqrt{1 - (v_r/c_r)^2}$,
 660 implying progressive acceleration of the rupture toward its limiting speed. In this frame-
 661 work, the theory predicts a decreasing size of the cohesive zone, ultimately tending to-
 662 ward a vanishing Λ for an idealized crack. In contrast, rough faults exhibit strong spa-
 663 tial variability in both the peak strength τ_p and residual strength τ_r . As a result, the
 664 breakdown stress drop $\Delta\tau_b$ also varies spatially, leading to local variations of associated
 665 stress intensity factors K_0 and K_c . These variations modulate the local rupture veloc-
 666 ity v_r and the cohesive-zone size Λ evolves heterogeneously during rupture propagation
 667 (Figure 8).

668 The evolution of Λ strongly depends on the rupture regime. In particular, confined
 669 ruptures exhibit significantly larger spatial fluctuations in Λ (Figure 8a–b) compared to
 670 runaway ruptures (Figure 8c). In the latter case, the progressive increase in rupture ve-
 671 locity v_r leads to a systematic reduction of Λ , resulting in a more spatially coherent trend
 672 with only limited local variability.

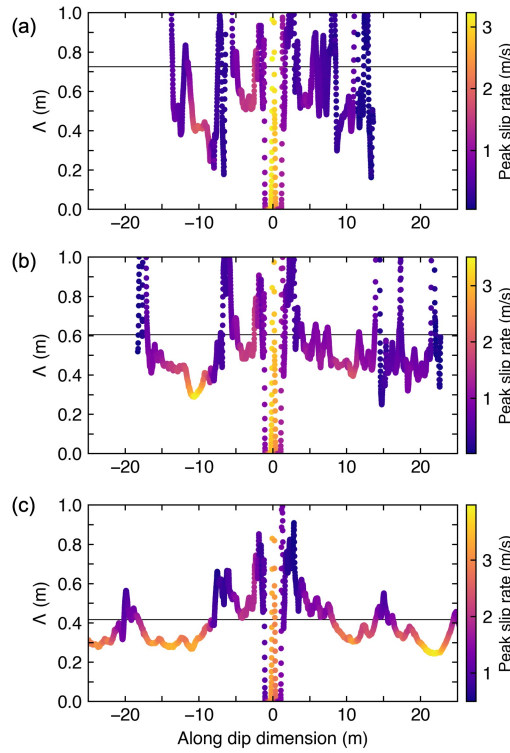


Figure 8. Cohesive zone evolution. **a)** Spatial distribution of the cohesive zone size Λ along a dip-section of the fault for the model with $\mu_d = 0.20$, $\lambda_{\max} = 20$ m, and $\alpha = 0.008$. **b)** Same as (a) but with $\mu_d = 0.19$. **c)** Same as (a) but with $\mu_d = 0.17$. In all panels, the colormap represents the peak slip rate along the section. The y-axis is limited to 1 m to better illustrate variations in cohesive-zone size; larger values are omitted.

673 The strongly heterogeneous rupture velocity, v_r , and the prevalence of pulse-like
 674 ruptures observed in confined events are accompanied by pronounced spatial variabil-
 675 ity in Λ . Their predominantly pulse-like propagation (Figure 2-3-4f) is consistent with
 676 rupture propagation being controlled by local stress and strength heterogeneities with
 677 reduced contributions from dynamic stress interactions among slipping points behind the
 678 crack-tip. Consequently, local variations in the breakdown stress drop and crack-driving
 679 force produce alternating local expansions and contractions of the cohesive zone, accom-

panied by spatially confined acceleration or deceleration of the rupture. Sharp spatial variations in Λ are associated with local variations in peak slip rate (Figure 8a–b), emphasizing the role of the cohesive zone in describing rupture front dynamics. However, under favorable conditions (e.g., low μ_d), where $K_0 \gg K_c$ over a significant spatial extent (Figure 7f), the rupture front propagates continuously and accelerates in a crack-like mode (Figure 4e). In this regime, Λ undergoes an overall reduction, associated with a coherent increase in peak slip rate (Figure 8c).

As expected from Equation 7, decreasing μ_d reduces Λ , as reflected by its decreasing spatial average (horizontal black lines in Figure 8). This implies that, for large μ_d , Λ remains greater than the minimum roughness wavelength, λ_{min} , whereas decreasing μ_d leads to comparable length scales, with $\Lambda \approx 0.4$ m and $\lambda_{min} = 0.4$ m.

Ruptures characterized by $\Lambda > \lambda_{min}$ exhibit strong spatial variability in cohesive zone size and pronounced heterogeneity (i.e., low correlation length; Figure 6b–e) in their dynamic features (v_r , peak slip rate, and pulse-like propagation). In contrast, when $\Lambda \sim \lambda_{min}$, a more coherent rupture behavior is generally observed (Figure 6h). Although shorter cohesive zones are expected to enhance sensitivity to smaller-scale heterogeneity (Barras et al., 2017), at first glance, the reduced variability associated with smaller Λ may be explained in our study by the small amplitudes of roughness for short λ . Moreover, according to Equation 7, the parameters controlling the cohesive zone size also govern the energy balance at the rupture front, affecting both K_0 and K_c . In our case, smaller values of cohesive zone size (Figure 8c) result in a larger ratio K_0/K_c (Figure 7e) because of decreasing μ_d yielding higher energy flow at the rupture front. These observations support the interpretation that the interaction between the rupture front and fault roughness is controlled by the ratio K_0/K_c . Specifically, a higher loading level at the rupture front (larger K_0) reduces the relative influence of fault roughness. This is because larger K_0 corresponds to greater stress drops, $\Delta\tau_d$, such that local variations in τ_0 and τ_r produce only minor perturbations to the ratio K_0/K_c .

Reducing μ_d to 0.17 yields exclusively run-away ruptures (Figure 5g–i). These ruptures accelerate or propagate at nearly constant speed, with overall higher rupture velocities compared to self-arresting cases (Figure 4d–e), and exhibit a decrease in the Hurst index H of the v_r PSD (Figure 4c), indicating an increased contribution of short-wavelength fluctuations in rupture velocity. This behavior is consistent with the reduction of Λ accompanying rupture acceleration: as Λ decreases, the rupture front becomes increasingly sensitive to smaller-scale heterogeneities.

5 Conclusions

Small earthquakes are often assumed to exhibit relatively simple rupture kinematics. However, increasing evidence suggests that rupture complexity also characterizes low-magnitude induced events (Wu et al., 2019; Király-Proag et al., 2019; Chen et al., 2026). Our 3D dynamic rupture simulations demonstrate that fluid-induced microearthquakes ($M_w < 1$) on rough faults can develop complex rupture kinematics despite their limited rupture dimensions. By systematically varying fault roughness and frictional properties, we identify two primary controls on rupture complexity and final rupture size. First, the fractal characteristics of fault roughness govern the spatial organization of stress heterogeneity, thereby modulating rupture-front acceleration, deceleration, and arrest. In particular, increasing the maximum wavelength of fault roughness enlarges the spatial extent of both favorably and unfavorably stressed regions, promoting a more effective asperity-barrier system (Das & Aki, 1977) and increasing the maximum attainable rupture size. Second, rupture dynamics are controlled by the competition between roughness-induced resistance and the energy available to sustain rupture propagation, both modulated by the spatial distribution of pore pressure. Larger roughness amplitudes and lower loading levels promote pulse-like, self-arresting ruptures, whereas smoother faults or higher

energy availability favor more coherent crack-like propagation with reduced rupture complexity.

These results reveal that fluid-induced microearthquakes need not be kinematically simple. Instead, our simulations show that self-similar rough faults driven by physically realistic injection-induced overpressure gradients are sufficient to generate rupture complexity comparable to that observed in laboratory earthquakes (Pozzi et al., 2025) and in tectonic earthquakes spanning several orders of magnitude larger scales (Ye et al., 2018).

Open Research Section

Simulations were performed using the open-source software SeisSol (Gabriel et al., 2025a) available on GitHub (<https://github.com/SeisSol/SeisSol>). Instructions for downloading, installing, and running the code are available in the SeisSol documentation at <https://seissol.readthedocs.io/>. Downloading and compiling instructions are at <https://seissol.readthedocs.io/en/latest/build-overview.html>. Instructions for setting up and running simulations are at <https://seissol.readthedocs.io/en/latest/configuration.html>. Quickstart containerized installations and introductory materials are provided in the docker container and jupyter notebooks at <https://github.com/SeisSol/Training>. Example problems and model configuration files are provided at <https://github.com/SeisSol/Examples>, many of which reproduce SCEC 3D Dynamic Rupture benchmark problems described at <https://strike.scec.org/cvws/benchmark.descriptions.html>. All input files to fully reproduce the results can be found in Mosconi (2026).

Conflict of Interest disclosure

The authors declare there are no conflicts of interest for this manuscript.

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Enter acknowledgments here. This section is to acknowledge funding, thank colleagues, enter any secondary affiliations, and so on.

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Supporting Information for ”Fault Roughness as a Driver of Rupture Complexity in Fluid-Induced Microearthquakes”

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Introduction

The Supplementary Material contains:

1. Supplementary Text S1 describes the details of the numerical method and computational meshes.
2. Supplementary Text S2 describes the procedure for creating the rough fault surface.
3. Supplementary Text S3 describes the nucleation procedure.
4. Supplementary Table S1 presents the complete parameter configuration and setup for the 3D dynamic rupture models.

September 3, 2026, 10:16am

5. Supplementary Text S4 describes the details of the pore fluid pressure profile calculation.

6. Supplementary Text S5 describes the method for fracture mechanics analysis.

Text S1. Numerical method and computational mesh

For the numerical simulations conducted in this study, we leveraged the advanced computational capabilities of SeisSol to capture the complex physical processes associated with induced seismicity. We employed high-order basis functions with a polynomial degree of $p = 5$, achieving $\mathcal{O}(h^6)$ accuracy and double precision in both spatial and temporal wave propagation for all simulations. This high spatial and temporal resolution is crucial for accurately capturing the detailed spatiotemporal evolution of rupture processes. The fine resolution is particularly important for modeling the variable cohesive zone size dictated by our frictional parameterization and stress conditions. In particular, Wollherr et al. (2018) proposed empirical criteria to adequately resolve the cohesive zone process based on $N_{c_{sub}}$, the number of sub-element points per median cohesive zone, defined as:

$$N_c^{sub} = N_c(p + 1). \quad (1)$$

Where N_c is the number of elements per median cohesive zone width and p is the polynomial degree of the basis function. As highlighted in the main text (Figure 8), the cohesive zone size varies with rupture speed; consequently, the number of points resolving the cohesive zone changes accordingly. To account for this, we use the 10th percentile of the median cohesive zone value (0.34 m) from the model with the lowest μ_d , which corresponds to the smallest median cohesive zone size. With an on-fault discretization of 0.2 m, this results in $N_{c_{sub}} = 10.2$, which exceeds the threshold of $N_{c_{sub}} > 9.9$ reported by

Wollherr et al. (2018) for the adequate resolution of the cohesive zone process. Therefore, we ensure sufficient resolution of the slip velocity and stress fields at the rupture front, which is essential for our analysis.

To optimize the computational process, we apply a scaling function to coarsen volume mesh element size, implementing a linear decrease in element size with distance from the fault plane, reaching 15 m element size at 250 m distance from the fault. SeisSol is optimized for the latest GPU architectures (Dorozhinskii & Bader, 2021; Dorozhinskii et al., 2024), enabling the use of a high-resolution mesh with approximately 35 million elements on the newly developed Leonardo cluster at CINECA. Using 48 nodes, each simulation ran for approximately 12 mins, achieving performance of 460 TFLOP/s.

Text S2 Rough fault surface

The non-planar fault geometry is modeled as a stochastic, band-limited self-affine random field following the general framework described in Shi and Day (2013). In the spatial domain, the fault topography can be mathematically defined by its height perturbations $h(\mathbf{x})$ relative to a reference nominal plane, where $\mathbf{x} = (x, y)$ denotes the two-dimensional position vector along the fault surface. The surface morphology is statistically characterized by its spatial pair correlation function $\langle h(\mathbf{x})h(0) \rangle$, which quantifies the geometric dependence between the elevations of any two points separated by a spatial lag $\mathbf{x}$.

The roughness power spectrum, or Power Spectral Density (PSD) function $P(\mathbf{k})$, is identified as the two-dimensional Fourier transform of the pair correlation function:

$$P(\mathbf{k}) = \frac{1}{(2\pi)^2} \iint_{-\infty}^{\infty} \langle h(\mathbf{x})h(0) \rangle e^{-i\mathbf{k}\mathbf{x}} d^2\mathbf{x} \quad (2)$$

where $\mathbf{k} = (k_x, k_y)$ represents the two-dimensional wavenumber vector. The power spectrum follows a characteristic power-law scaling behavior that dictates the energy distribution across different spatial scales:

$$P(\mathbf{k}) = C_0 |\mathbf{k}|^{-2(H+1)} \quad (3)$$

where $k = |\mathbf{k}| = \sqrt{k_x^2 + k_y^2}$ is the radial wavenumber magnitude, C_0 is a scaling constant, and H is the Hurst exponent ($0 \leq H \leq 1$) which governs the spectral fall-off rate. A perfectly self-similar fault topography is assumed by setting $H = 1$.

For practical computational setups, the generated random field is band-limited due to discrete spatial resolution limits. The spectrum is truncated between a low-wavenumber cutoff $k_{\min} = 2\pi/\lambda_{\max}$ and a high-wavenumber cutoff $k_{\max} = 2\pi/\lambda_{\min}$. Finally, the absolute scale of the topography is constrained using the root-mean-square (RMS) roughness height h_{rms} , which is dominated by the longest wavelengths of the self-affine spectrum and follows the scaling law:

$$h_{\text{rms}} = \alpha \lambda_{\max}^H \quad (4)$$

where α is the non-dimensional amplitude-to-wavelength ratio. The empirical sample standard deviation of the synthesized discrete array is linearly rescaled to exactly match this target h_{rms} value, yielding a physically consistent non-planar boundary condition for dynamic rupture modeling.

Text S3. Nucleation procedure

In all models, the rupture is artificially nucleated at $(x, z) = (0, 0)$ m using a small circular patch with a radius of 1 m, where a Gaussian overstress of 5 MPa is superimposed on the background initial shear stress, τ_0 . The use of such a small nucleation patch is made

possible by the fluid-induced earthquake framework, in which elevated pore pressure at the nucleation point reduces the effective normal stress. This facilitates rupture initiation by allowing the rupture front to reach sufficiently high shear stress and accelerate during the early stages of propagation.

Table S1: Summary of model parameters used in the 3D dynamic rupture simulations.

Category	Parameter	Value(s)	Unit
<i>Elastic medium</i>			
Compressional wave velocity	α	2612	m s^{-1}
Shear wave velocity	β	1513	m s^{-1}
Density	ρ	2620	kg m^{-3}
<i>Fault geometry</i>			
Fault type	—	Normal fault	—
Dip angle	—	60	deg
Fault dimensions	$L \times W$	60×50	m
Computational domain	—	$250 \times 250 \times 250$	—
<i>Fault roughness</i>			
Roughness model	—	Self-similar, band-limited	—
Hurst exponent	H	1.0	—
Minimum wavelength	$\lambda_{\min}$	0.40	m
Maximum wavelength	$\lambda_{\max}$	20, 25, 30, 35, 40	m
Amplitude-to-wavelength ratio	α	0.004, 0.006, 0.008	—
Number of realizations (seeds)	—	31 per parameter set	—
<i>Stress conditions</i>			
Minimum horizontal stress	S_h	20	MPa
Maximum horizontal stress	S_H	25	MPa
Vertical stress	S_v	31	MPa
Initial normal stress (planar fault)	σ_n	22.7	MPa
Initial shear stress (planar fault)	τ_0	4.7	MPa
Stress regime	—	Normal faulting ($S_h < S_H < S_v$)	—
<i>Pore pressure</i>			
Pore-pressure field	p_f	From TOUGH3–FLAC3D	MPa
Injection configuration	—	Injection in the fault center	—
<i>Friction law</i>			
Constitutive law	—	Linear slip-weakening	—
Static friction coefficient	μ_s	0.58	—
Dynamic friction coefficient	μ_d	0.20, 0.19, 0.17	—
Critical slip distance	d_c	0.6	mm
<i>Rupture nucleation</i>			
Nucleation style	—	Forced overstress	—

Continued on next page

Table S1 – Continued from previous page

Category	Parameter	Value(s)	Unit
Nucleation patch size	–	1	m
Nucleation location	–	Fault center (injection point)	–

Text S4. Fluid diffusion computation

In order to create realistic pressure conditions on the fault zone, we employ the software TOUGH3-FLAC3D, that allows the simulation of coupled fluid flow and geomechanics (Rinaldi et al., 2022). This approach aims at simulating complex non-linear behavior potentially occurring in the vicinity of the injection point, as well effects of a packed interval. The coupled approach allows us to account for full poroelasticity via porosity evolution as well as variation of permeability as function of geomechanical parameters (e.g. stress or strain). We develop a first-order model (50 m X 50 m X 50 m) with a fault zone dipping 60°, 20 cm thick, and cutting through an homogenous medium. Initial conditions follow the state of stress found at the BedrettoLab, with minimum horizontal stress at 20 MPa, maximum horizontal stress at 25 MPa, and vertical stress at 31 MPa for the injection region, as in the the dynamic rupture model configuration. The initial pore pressure at the injection is set at 3.8 MPa. We impose constant stress and pressure at all boundaries. In terms of rock properties, the fault zone is assumed weaker than the surrounding formation, with a Young’s modulus of 5 GPa compared to 15 GPa of the host rock. The Poisson’s ratio is set to 0.25 in the entire domain. We neglect poroelastic effects by assuming a near-zero Biot’s coefficient (0.001). The permeability of the fault zone is assumed constant at 10^{-15} m^2 , representing a fractured region within homogeneous granite with permeability set at 10^{-18} m^2 . The injection region at the center of the model is set as a 1 m^2 patch, with permeability changing as a function of the normal effective stress.

Porosity is set to 1% in the entire domain. We simulate 24 hours of injection at constant flow rate (0.012 kg/s), simulating a constant pressure of about 14.5 MPa at the injection point, and allowing fluids to propagate along the fault. In TOUGH3-FLAC3D, the given conditions would reactivate the fault within the next numerical time step with a further increase in pressure when assuming a fault zone with a friction angle of 31° , yielding a static friction coefficient of 0.6 very similar to the value adopted for dynamic simulations (0.58). Hence, we stop our simulation at the time step before earthquake nucleation on the fault would occur. The simulated pressure profile (Figure 1c) is then used as the starting point for the dynamic rupture model and it is considered representative of key physical conditions during direct injection into a fault zone.

Text S5. Fracture mechanics method

To estimate the rupture front energy balance of our 3D dynamic rupture models, for spatially varying (not time-dependent) dynamic stress drop $\Delta\tau_d(r)$, we can describe our problem as a classical shear crack in the theory of Linear Elastic Fracture Mechanics (LEFM). The same approach is already adopted in several works in the literature concerning induced seismicity (Garagash & Germanovich, 2012; Galis et al., 2017; Ciardo & Rinaldi, 2021; Saez & Lecampion, 2022). The fundamental concept introduced by LEFM is that the advancement of the crack tip requires a balance between the strain energy released in the body, due to the cracked surface (G_0), which flows toward the crack tip, and the energy dissipated to advance the crack tip itself (G_c). The energy balance can, therefore, be formulated, in a static manner, as:

$$G_0 = \frac{K_0^2}{2\mu'} = G_c \quad (5)$$

Where $\mu' = \mu$ in case of mode III direction and $\mu' = \mu/(1 - \nu)$ in mode II direction, with ν the Poisson coefficient, while K_0 is the static stress intensity factor that quantify the intensity of the singular stress field in the vicinity of the crack-tip, that is for a penny-shaped crack configuration (Rice, 1968):

$$K_0(\mathcal{L}) = \frac{2}{\pi\sqrt{\mathcal{L}}} \int_0^{\mathcal{L}} \frac{\Delta\tau_d(\ell)}{\sqrt{\mathcal{L}^2 - \ell^2}} \ell \, d\ell \quad (6)$$

here $\mathcal{L}$ is the crack radius and ℓ is the distance from the center of the crack, serving as the integration variable. The fracture energy is related to the fracture toughness (K_c) trough

$$K_c = \sqrt{2\mu G_c} \quad (7)$$

thus the rewritten energy balance in the Irwin's form is $K_0 = K_c$ as adopted in the main text analysis.

References

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